STK 9 DIFFERENCES RESULTING FROM USING SPICE-BASED JPL DE421 PLANETARY EPHEMERIDES

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AGI has changed the default behavior of STK 9 when providing planetary positions and orientations to reflect the availability of updated ephemerides and to better support planet-centric positioning. The numerical differences, and their operational causes, are discussed.

INTRODUCTION

The Developmental Ephemeris DE405 / LE405 ephemerides have been the basic planetary and lunar ephemerides used for the Astronomical Almanac since the adoption of the ICRF in 2003. However, the DE405 lunar orbit was not fit in a way that was consistent with the other planets. The DE421 combines the fit of lunar laser ranging (LLR) and planetary measurements and is recommended for high accuracy lunar navigation purposes by its originators. [1, 2] Since the DE421 planetary and lunar ephemerides now represent the "current best estimates" of the orbits of the Moon and planets, they are now used by default to provide locations of solar-system objects in Satellite Tool Kit version 9.0 (STK 9).

The Developmental Ephemeris is generated from a numerical integration of the solar system, using barycentric positions for the outer planets and including effects from general relativity. The ephemerides is made available to the public from a JPL website. AGI has collected the ephemerides for the period 1960-2050 and packaged it into a JPL DE file, a particular binary format that allows software (publicly available from JPL) to extract and interpolate the data.

JPL also makes available ephemerides in another format called SPICE. There are SPICE files that contain the same developmental ephemerides as normally shipped in a DE file. In addition, JPL makes available ephemerides for a wide range of celestial bodies in the solar system. These ephemerides are usually developed during JPL mission planning and operations. Time spans for different bodies can vary widely; moreover, there may be several versions of ephemerides for the same celestial body developed at different times (and possibly incorporating different sets of data). For example, the ephemerides for the Jovian system were updated and improved during the Galileo mission.

SPICE files are read and interpolated using SPICE software available from JPL. AGI has incorporated those parts of SPICE dealing with ephemeris interpolation into its software. AGI has also collected together into a few SPICE files the best ephemerides available for many of the lar-

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ger bodies of the solar system. Note that JPL does not publish a solar system SPICE file of its own.

Currently, all central bodies shipped with AGI software could be configured to use the ephemerides from SPICE files. However, the older DE file format provides better time precision when requesting interpolated ephemeris. Thus, the Earth, Moon, and Sun are configured to use the older DE file format as their ephemeris source; all other bodies (except for Ceres) use ephemerides contained in SPICE files. Ceres uses a simple analytic formula (essentially a two-body formula where the elements drift linearly in time).

In addition to central bodies, STK makes available Planet objects to model celestial bodies. The ephemeris for a Planet object may be configured in one of several ways. The *Default* option indicates to the software that the Planet's ephemeris should coincide with the ephemeris for the central body of the same name. Thus, since the Sun central body uses the DE file, a Planet object created for the Sun using the *Default* option will also use the DE file. Similarly, a Planet object created for Europa using the *Default* option will use SPICE as its ephemeris source since the Europa central body uses SPICE. When the Planet object's option is set to *Spice*, the JPL SPICE toolkit is used to interpolate the ephemeris from the DE421-based SPICE file set. When the Planet object's option is set to *DE421*, then the JPL DE421 file is used as the ephemeris source. Some Planet objects also support *Analytic*, in which the ephemeris is approximated using a set of osculating orbital elements and element rates (usually contained in a file describing the corresponding central body).

OPERATIONAL DIFFERENCES BETWEEN DE405 AND DE421-BASED SPICE TOOLKIT

The JPL DE option was previously the default behavior for all planetary bodies (including Pluto) whereas the SPICE toolkit was primarily available for planetary satellites (moons). Under STK 9, the SPICE toolkit option is default for all planets, excluding the Moon, Earth, and Sun, which still default to the JPL DE option. There are some operational differences resulting from the transition of STK 8's use of DE405 ephemerides to STK 9's use of the DE421-based SPICE toolkit when providing default planetary locations.

- The JPL DE option provides the physical location of the barycenter of a planetary system, whereas the SPICE toolkit option can provide both the physical location of the center of the planet and the barycenter (where appropriate). Thus, the outer planets in STK 9 locate the planetocentric location in contrast to STK 8 where the barycentric locations were used.
- In STK 9, the independent variable used to evaluate the JPL DE and the SPICE toolkit is Barycentric Dynamical Time (TDB), related to Terrestrial (Dynamical) Time (TT[*]) by the following conventional relationship:[†]

$$\text{TDB} - \text{TT} = 0^{s}.001657 \sin(E) \tag{1}$$

where

[*] An older notation for TT is TDT.
[†] http://sohowww.nascom.nasa.gov/solarsoft/stereo/gen/exe/icy/doc/time.req

$$E = M + 1.671\text{D-}2 \sin(M), \quad (2)$$

and

$$M = 6.239996 + 1.99096871\text{D-}7\ (\text{JD} - 2451545.0), \quad (3)$$

where JD is Julian date (TT). This relationship is consistent with the one used with the SPICE toolkit. In previous versions of STK, TT was used as the independent variable by default when using any JPL DE file, since the two times are nearly equivalent on average.*

- The SPICE toolkit option uses a single-word variable for time, while the JPL DE option uses a more-precise two-word variable for time. Thus, numerical differences could potentially result simply due to the differing precision of the independent variable.
- The installed SPICE file set generally provides data from 1 Jan 1990 0h UTC to 30 Dec 2048 0h UTC, although there are some exceptions, as illustrated in Table 1. The JPL DE421 file provides data from 23 Dec 1958 0h TT to 2 Jan 2050 0h TT.

ICRF versus J2000 Reference Frames

The JPL DE400-series ephemerides have all been oriented onto the ICRF. JPL ephemerides prior to the DE400 series were referenced to the mean equator and equinox of J2000. The difference between the ICRF and the mean equator and equinox of J2000 is intentionally small – to within the uncertainty of the former frame and on the order of tens of milliarcseconds. Because of this, some agencies still refer to the JPL DE400 series as being relative to the mean equator and equinox of J2000, or simply "J2000".

Prior to version 9, STK documentation also labeled the directional origin of the JPL DE405 as the mean equator and equinox of J2000. Starting with STK 9, the J2000 and ICRF are maintained as distinctly separate references frames, and the JPL DE400-series reference frame is precisely identified as the ICRF.

Because the JPL DE400-series has always been referenced to the ICRF, no significant differences can be attributed to reference frame when comparing the "J2000" DE405 planetary positions of STK 8 with the "ICRF" DE421 planetary positions of STK 9. Rather, the differences are mainly due to the fact that improved observational information was added to the later ephemerides.

STK 9 must correctly interpret older files (version 8 and earlier) that use the label “J2000” to indicate a coordinate system, since STK 9 distinguishes between these frames whereas earlier versions did not. The correct interpretation is to treat “J2000” from an earlier file as “ICRF” in STK 9 for all central bodies other than Earth. For Earth, the correct interpretation is to treat “J2000” in an earlier version as “J2000” in STK 9.

* On average, the TDB and TT meter are approximately the same. STK employs the reported TDB meters as if they were TT meters and does not attempt to rescale interplanetary distances due to relativistic differences between TDB and TT coordinates (understanding that rescaling of distance is likely an uncommon, and therefore unexpected, practice).

Table 1. STK Central Body Attributes

Central Body	*Spice ID*	*STK8 Default Source*	*STK9 Default Source*	*IAU Rotation Source*	*Default Start 0h UTC*	*Default End 0h UTC*
Sun	10	DE	DE	2006	23 Dec 1958♦	2 Jan 2050♦
Mercury	199	DE	Spice	2000	1 Jan 1990	30 Dec 2048
Venus	299	DE	Spice	2000	1 Jan 1990	30 Dec 2048
Earth	399	DE	DE	IERS EOP	23 Dec 1958♦	2 Jan 2050♦
Moon	301	DE	DE	2000	23 Dec 1958♦	2 Jan 2050♦
Mars	499	DE	Spice	2000	1 Jan 1990	30 Dec 2048
Phobos	401	Spice	Spice	2000	1 Jan 1990	30 Dec 2048
Deimos	402	Spice	Spice	2000	1 Jan 1990	30 Dec 2048
Ceres	2000001	Analytic	Analytic	2000	—	—
Jupiter	599	DE	Spice	2006	1 Jan 2000♦	30 Dec 2048
Io	501	Spice	Spice	2000	1 Jan 2000♦	30 Dec 2048
Europa	502	Spice	Spice	2000	1 Jan 2000♦	30 Dec 2048
Ganymede	503	Spice	Spice	2000	1 Jan 2000♦	30 Dec 2048
Callisto	504	—	Spice	2000	1 Jan 2000♦	30 Dec 2048
Saturn	699	DE	Spice	2000	1 Jan 1990	30 Dec 2048
Mimas	601	—	Spice	2006	1 Jan 1990	30 Dec 2048
Enceladus	602	—	Spice	2006	1 Jan 1990	30 Dec 2048
Tethys	603	—	Spice	2006	1 Jan 1990	30 Dec 2048
Dione	604	—	Spice	2006	1 Jan 1990	30 Dec 2048
Rhea	605	—	Spice	2006	1 Jan 1990	30 Dec 2048
Titan	606	Spice	Spice	2000	1 Jan 1990	30 Dec 2048
Hyperion	607	—	Spice	—	1 Jan 1990	30 Dec 2048
Iapetus	608	—	Spice	2000	1 Jan 1990	30 Dec 2048
Phoebe	609	—	Spice	2006	1 Jan 1990	30 Dec 2048
Uranus	799	DE	Spice	2000	1 Jan 1990	30 Dec 2048
Ariel	701	—	Spice	2000	1 Jan 1990	30 Dec 2048
Titania	703	—	Spice	2000	1 Jan 1990	30 Dec 2048
Neptune	899	DE	Spice	2000	1 Jan 1990	30 Dec 2048♦
Triton	801	Spice	Spice	2000	1 Jan 1990	30 Dec 2048
Charon	901	Spice	Spice	2006	1 Jan 1990	30 Dec 2048
Pluto	999	DE	Spice	2006	1 Jan 1990	30 Dec 2048

♦ *0h TAI*

IAU Planetary Orientation Models

Every three years the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements revise the reported directions of the rotational poles and the prime meridians of the planets, satellites, and asteroids. Central bodies in STK generally use these reported values to orient its modeling of surface objects. The 2000 report is the primary basis of STK 8.[3] The rotational elements of the Sun, Jupiter, Pluto, Charon, and seven Saturnian satellites (moons) were updated in 2006 (Table 1) and this is reflected in the default behavior of STK 9.[4]

STK 9 treats the rotational elements of celestial bodies within the solar system as being relative to the ICRF. The 2000 report clarifies that the "reference frame now used is the International Celestial Reference Frame (ICRF)" and the 2006 report are also relative to the ICRF.

NUMERICAL DIFFERENCES BETWEEN DE405 AND DE421-BASED SPICE TOOLKIT

Relative to the scale of the solar system, the differences between the JPL DE405 and the DE421-based SPICE toolkit are quite small. Users may expect angular heliocentric differences on the order of a fraction of a second of arc for the outer solar system, and angular heliocentric differences on the order of a few milliarcseconds within the inner solar system. Maximum heliocentric differences in radial planetary distances within the inner solar system are on the order of meters, while heliocentric differences of the outer solar system are on the order of hundreds of kilometers. Average and maximum absolute differences are presented in Table 2.

Table 2. Average and Maximum Absolute Differences (Heliocentric)

	Average Difference (DE405 minus DE421)			Maximum Absolute Difference (DE405 minus DE421)		
Celestial Body	Latitude (")	Longitude (")	Distance (km)	Latitude (")	Longitude (")	Distance (km)
Mercury	0.0010	0.0031	0.019	0.0054	0.0076	0.333
Venus	0.0000	0.0008	-0.005	0.0021	0.0015	0.050
Earth	0.0000	0.0010	-0.010	0.0017	0.0016	0.029
Moon	0.0000	0.0010	-0.010	0.0017	0.0016	0.038
Mars	0.0000	0.0007	-0.013	0.0015	0.0012	0.040
Phobos	0.0000	0.0013	-0.073	0.0083	0.0145	13.545
Deimos	-0.0009	0.0010	-0.160	0.0608	0.0678	70.869
Ceres	—	—	—	—	—	—
Jupiter	0.0038	0.0223	-6.313	0.0492	0.0943	232.351
Io	0.0038	0.0222	-6.428	0.0304	0.0391	17.310
Europa	0.0038	0.0222	-6.424	0.0314	0.0393	17.270
Ganymede	0.0038	0.0222	-6.422	0.0295	0.0390	17.116
Saturn	0.0247	-0.1084	25.266	0.0582	0.1808	566.266
Titan	0.0256	-0.1062	16.902	0.0614	0.1760	587.420
Uranus	0.0749	0.0805	-358.165	0.0937	0.0895	622.124
Neptune	0.0247	-0.0276	2236.447	0.0318	0.0832	3154.821
Triton	0.0083	-0.0595	3897.267	0.0147	0.1547	4963.120
Pluto	0.0162	0.0816	-7468.775	0.1171	0.2798	12887.042
Charon	-0.1138	-0.1774	270.554	0.1602	0.2469	3188.665

Lunar Orientation Model

The central-body-fixed frame for the Moon is related to the ICRF through Euler angles extracted from the JPL DE files, including lunar librations. In STK 8, the central-body-fixed frame is implicitly that of the principal-axis (PA) system, sometimes known as the axis-of-figure system. Beginning with STK 9, a distinction is made between the PA system and the so-called mean-Earth/rotation axes (ME) system. The ME system is the recommended coordinate system for providing topographic coordinates, and defines the reference frame to which almost all lunar cartographic products are aligned. The PA system, however, remains the basis of the lunar gravity field. The two frames can be related by the constant rotational sequence when dealing with the DE421 ephemerides:

$$\mathbf{r}_{PA} = R_z(67''.92)\, R_y(78''.56)\, R_x(0''.30)\, \mathbf{r}_{ME} \tag{4}$$

$$\mathbf{r}_{ME} = R_x(-0''.30)\, R_y(-78''.56)\, R_z(-67''.92)\, \mathbf{r}_{PA} \quad (5)$$

NOTE: While the ME frame is now the lunar Fixed frame, it is not the Fixed frame used when evaluating the gravitational field when using high-fidelity force models (say, as part of a numerical integration of a trajectory about the Moon). JPL continues to recommend the use of the lunar PA frame, based upon the definition in the DE 403 file, for the evaluation of lunar gravitational fields. Since STK can load only one DE file at a time, and is defaulted to use the DE421 file, STK realizes the PA 403 frame through its defined relationship to the lunar ME frame.

EXAMPLE

To illustrate the combined effects of changing certain ephemeris defaults between STK 8 and STK 9, a scenario was created spanning the total lunar eclipse of 21-Feb-2008. A facility was established at the coordinates of the Apollo 11 Lunar Laser Retroreflector (0°.67337 N. latitude, 23°.47293 E. longitude, ME-system), and the line-of-sight access to the Sun was computed. The reported stop and start times of solar access, which corresponds to the computed start and stop times of apparent total eclipse at the lunar site, are reported in Table 3.

Table 3. Differences in Reported Total Eclipse at Apollo 11 LLR During 21-Feb-2008 Eclipse

Version	Eclipse Start Time (UTC)	Eclipse Stop Time (UTC)
STK 9	21 Feb 2008 01:52:56.063	21 Feb 2008 05:18:19.481
STK 9, TDB used w/ JPL DE	21 Feb 2008 01:52:56.061	21 Feb 2008 05:18:19.480
STK 8, ME site adjusted for PA	21 Feb 2008 01:52:56.060	21 Feb 2008 05:18:19.478
STK 8, ME site unadjusted for PA	21 Feb 2008 01:52:56.830	21 Feb 2008 05:18:19.610

The differences between STK 8 and STK 9 eclipse timing are approximately 0.77 seconds in start time, and 0.13 seconds in stop time, if the retroreflector's original ME-system coordinates remain unadjusted for use in the PA-system that is implicit to STK 8. When an adjustment is made to the ME-system coordinates using Equation 5, the resulting PA-system coordinates become 0°.69350 N. latitude and 23°.45529 E. longitude. Using these PA-adjusted values in STK 8, the net effect of the updates in the JPL DE modeling of Earth and Moon positions between STK 8 and STK 9 is approximately 2 ms.

CONCLUSION

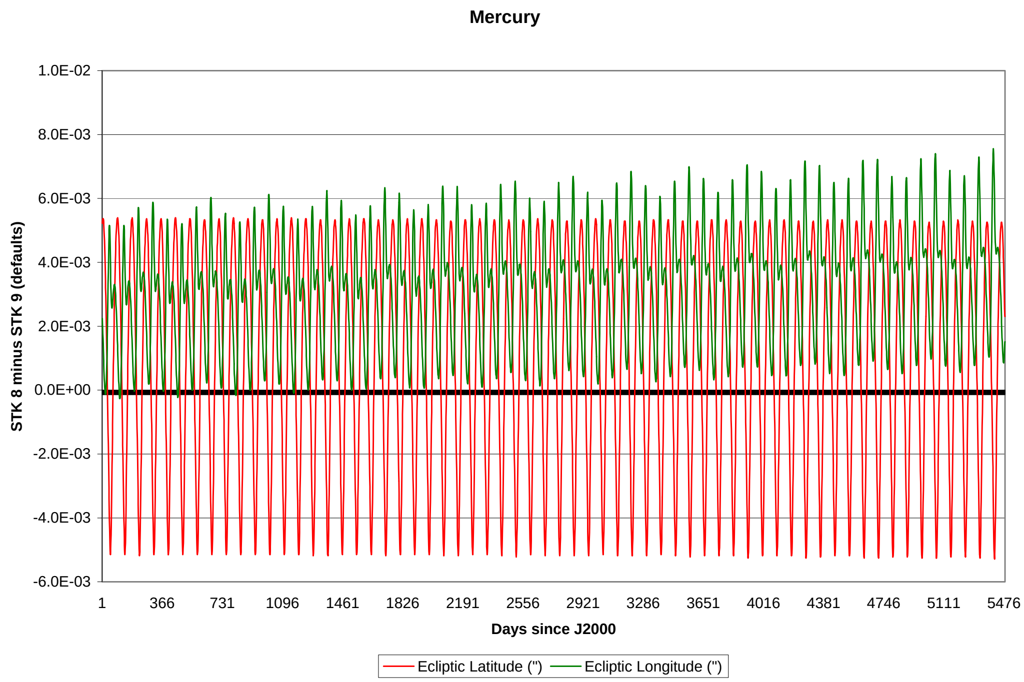
AGI has updated some default behaviors in STK 9 when providing planetary positions and orientations. These changes reflect the availability of updated ephemerides and better support the reporting of planet centers and lunar topography. Numerical differences have been illustrated and their operational causes have been discussed. Some of the causes include:

- an update from the JPL DE405 to the DE421 planetary ephemeris via the SPICE toolkit,
- a change from the PA system to the ME system for lunar Fixed frame,
- the native reporting of planetary centers via the SPICE toolkit, rather than barycenters of planetary systems from a DE file,

- a formal change of inertial basis from "J2000" to the ICRF (which slightly affects the reported orientation of the Earth but has no real effect on planetary positioning),

The level of differences are presumed to be small, if not negligible, for most typical STK-use cases. For the sake of completeness, the appendix contains plots of the reported default positions of central bodies common to STK 8 and STK 9.

APPENDIX: CENTRAL-BODY POSITION DIFFERENCES (2000-2015)



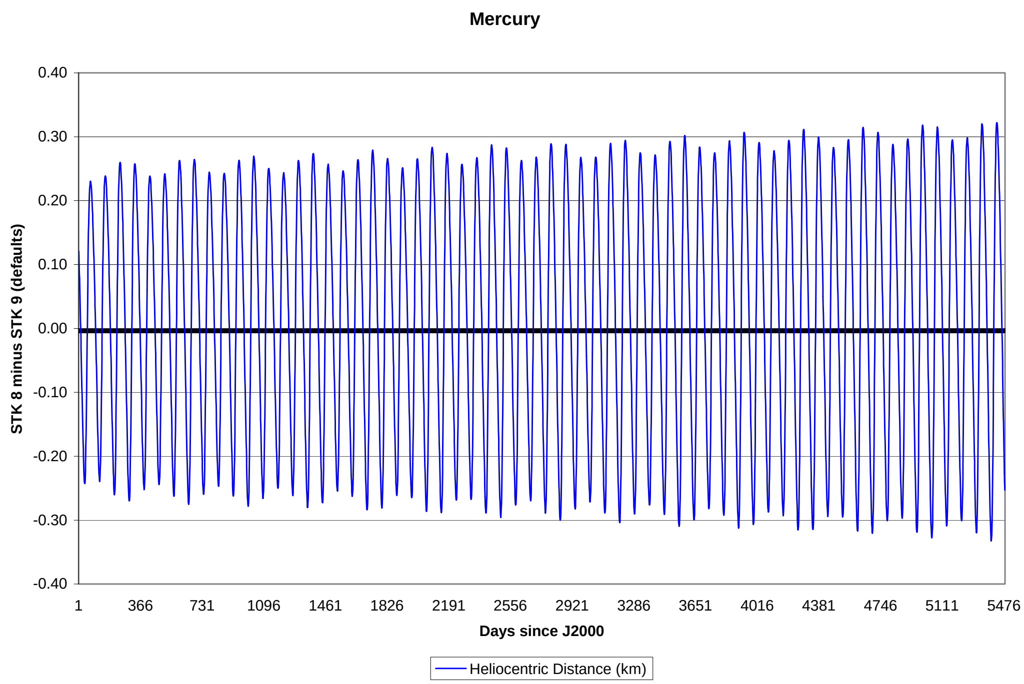
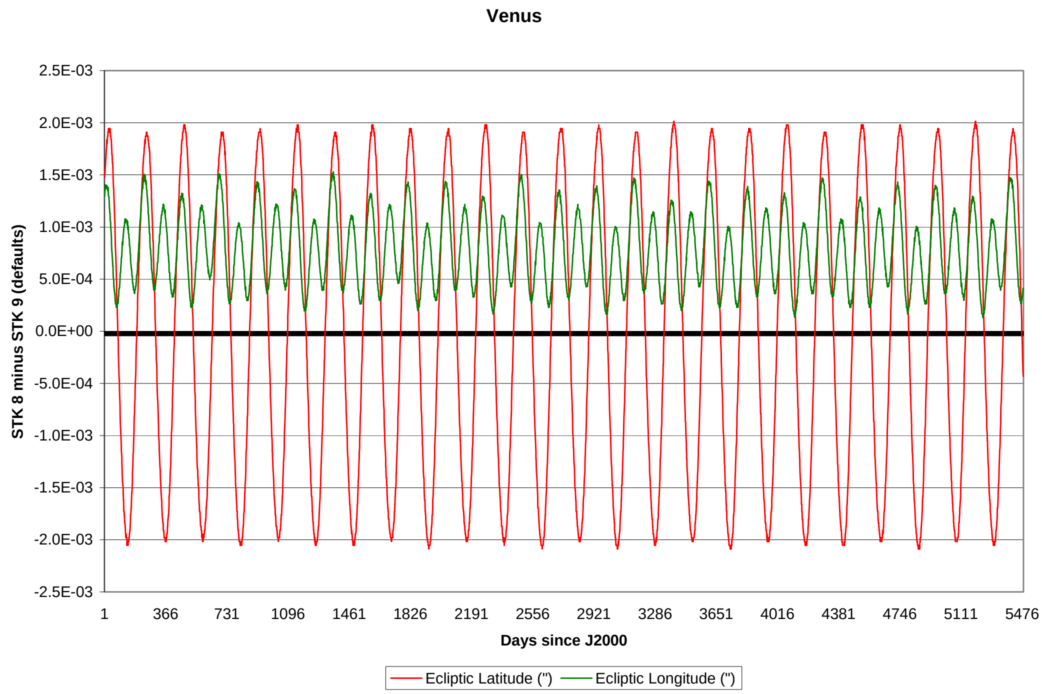


Figure 1. Differences in Reported Mercury Position (2000-2015)



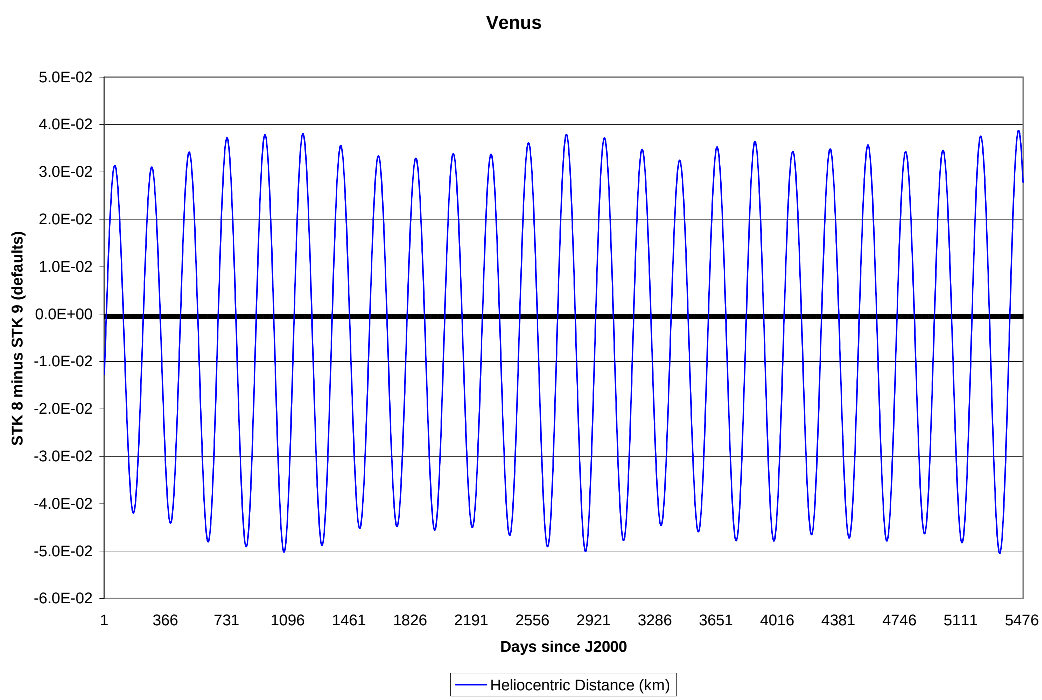
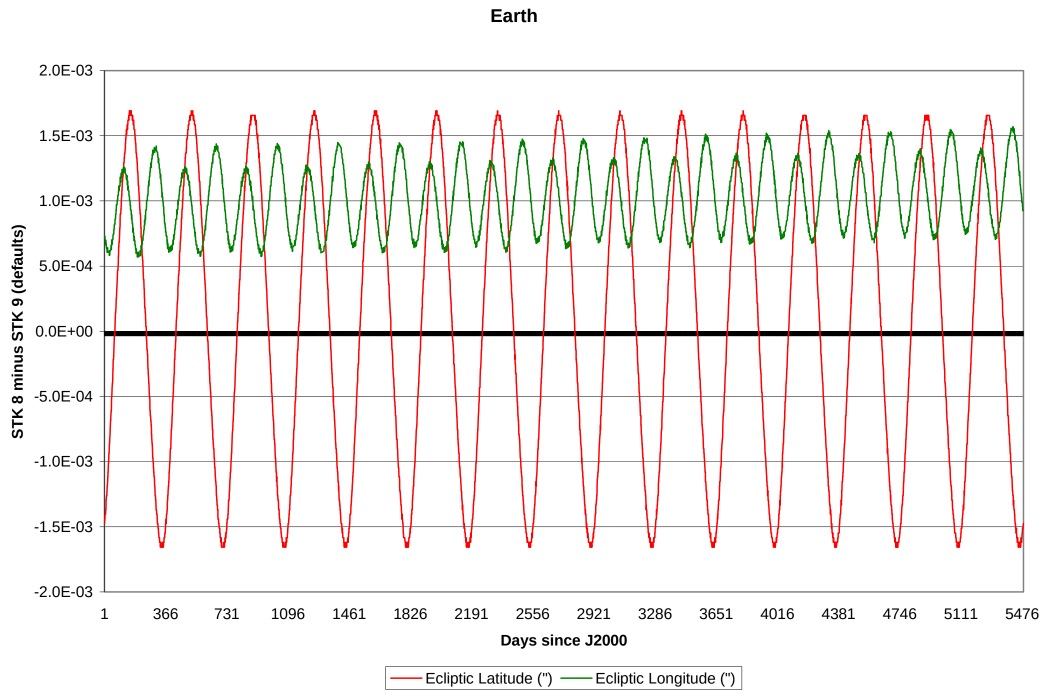


Figure 2. Differences in Reported Venus Position (2000-2015)



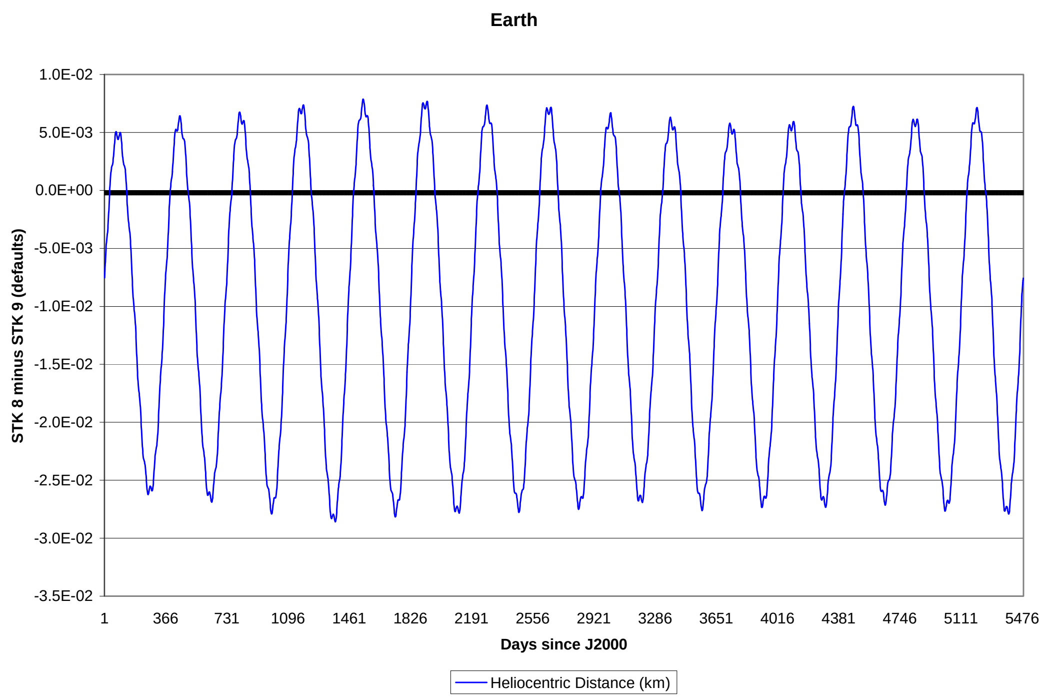
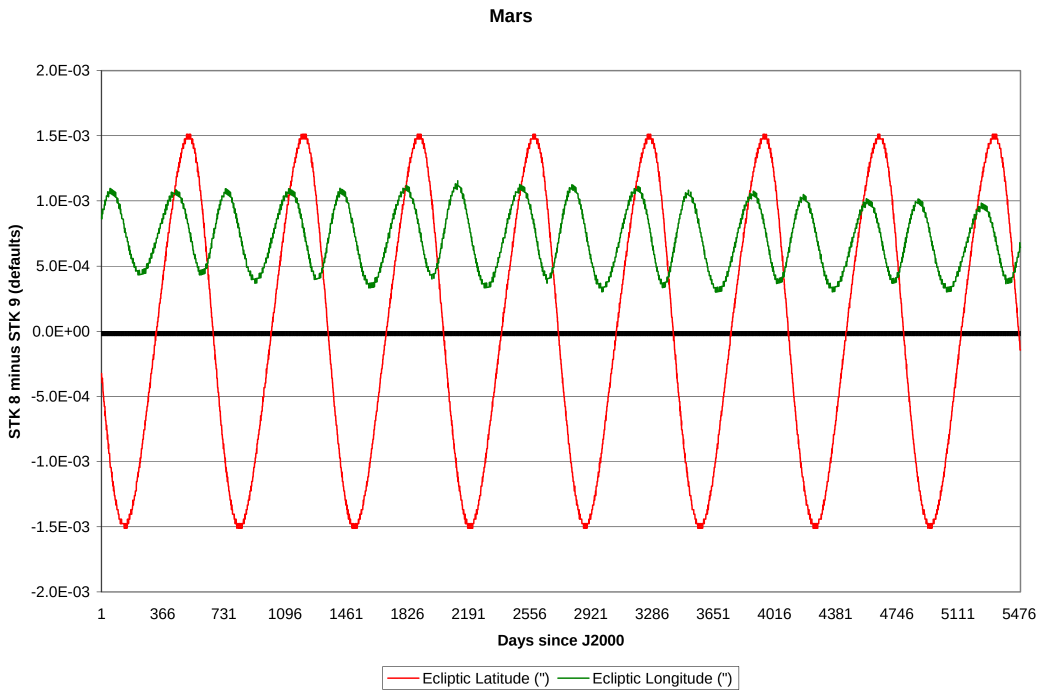


Figure 3. Differences in Reported Earth Position (2000-2015)



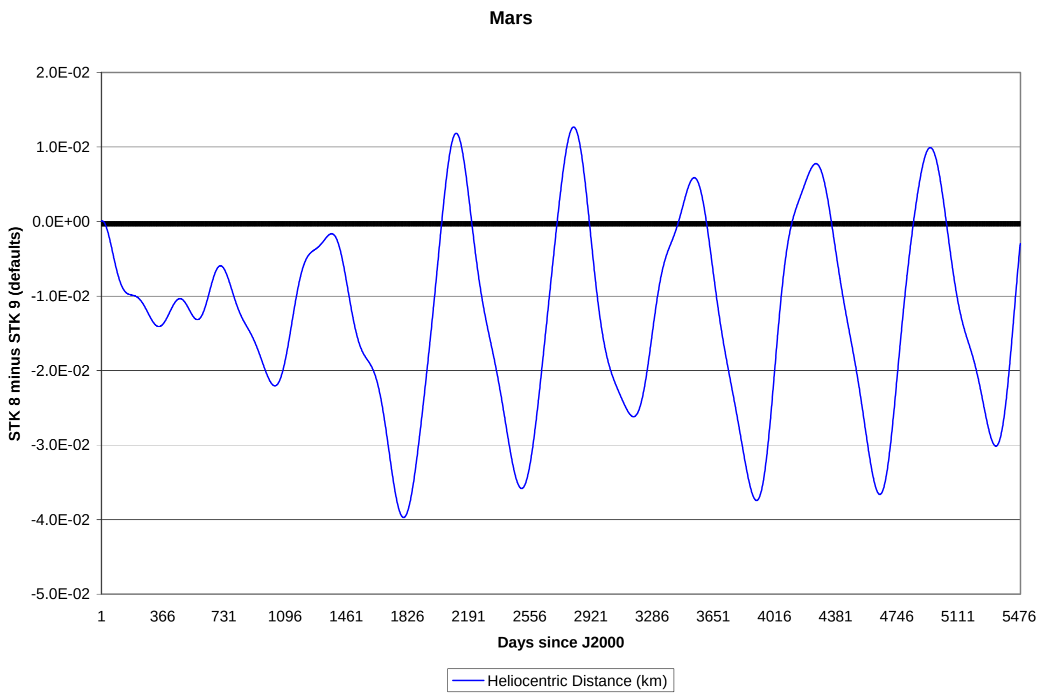
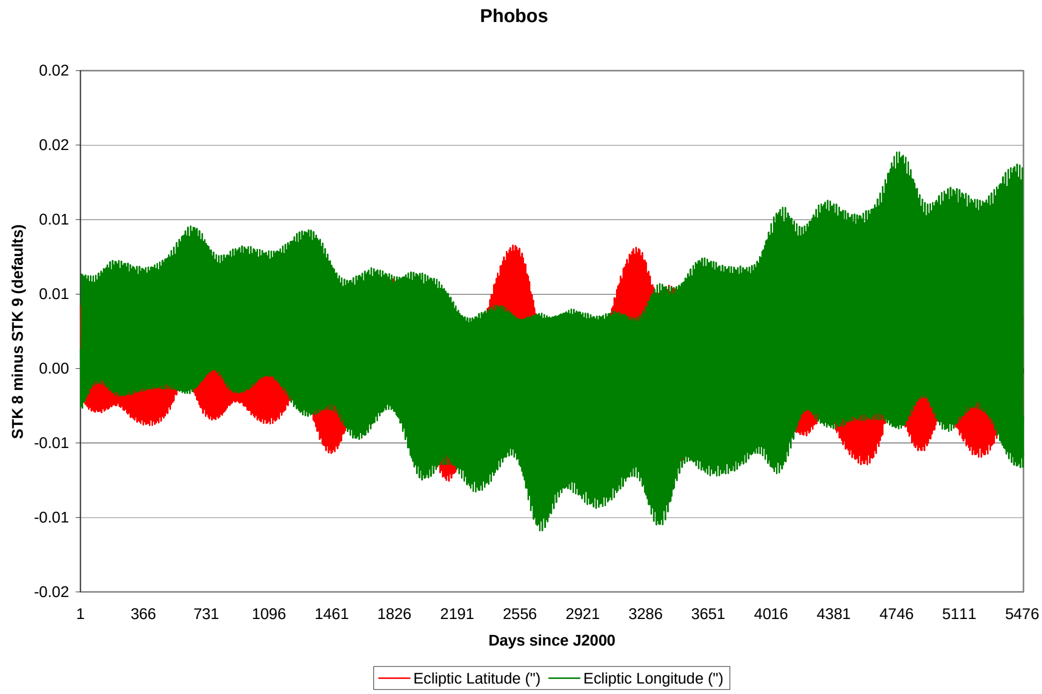


Figure 4. Differences in Reported Mars Position (2000-2015)



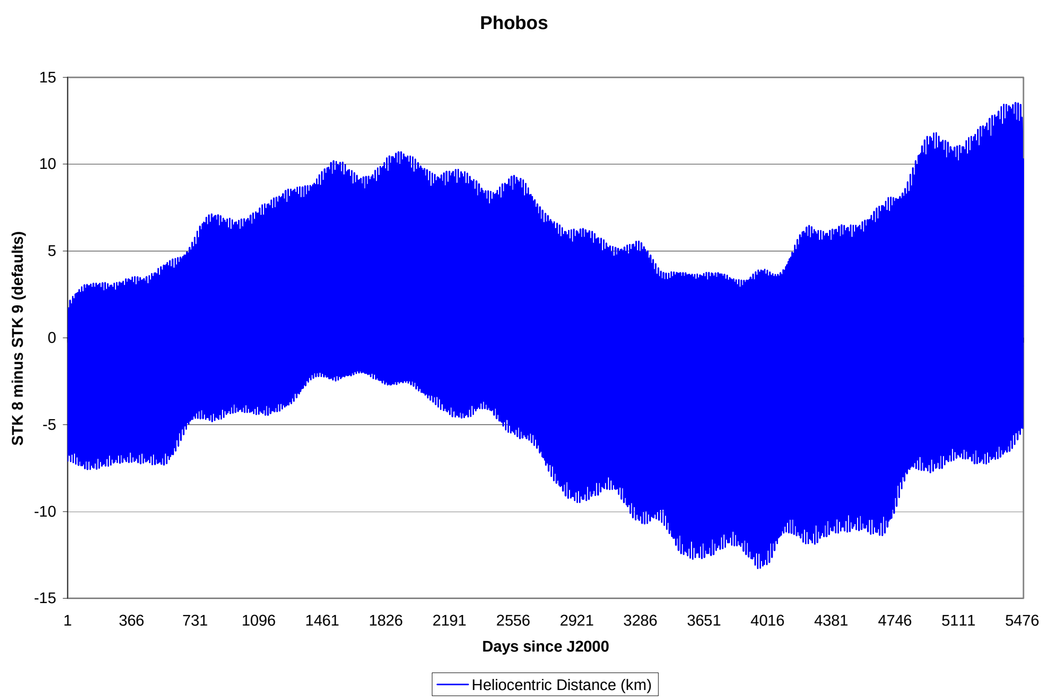
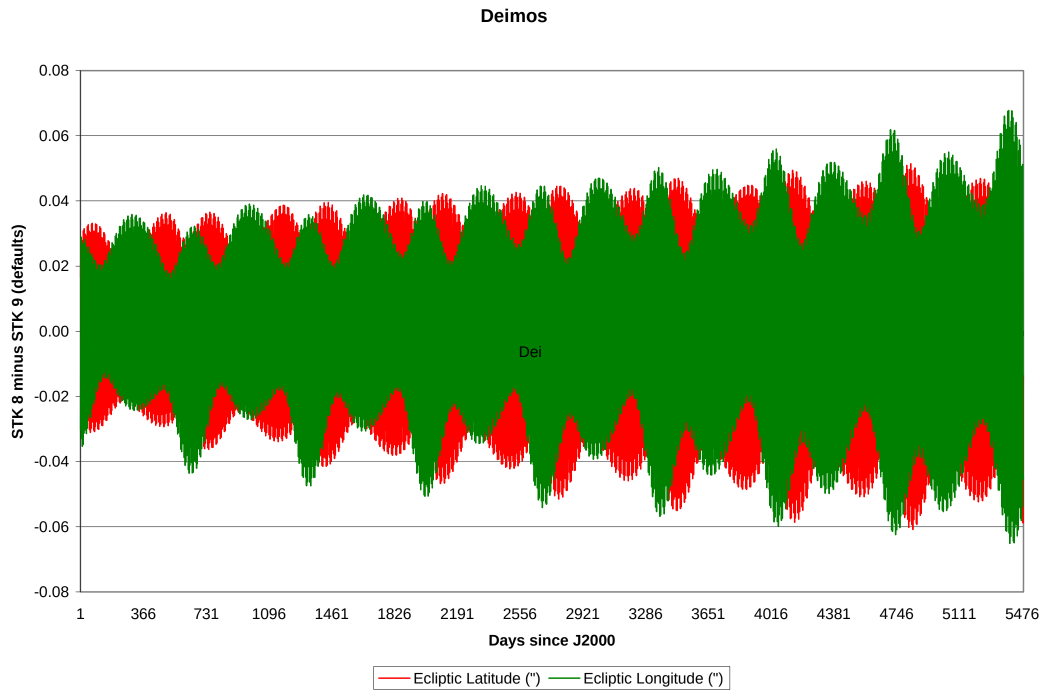


Figure 5. Differences in Reported Phobos Position (2000-2015)



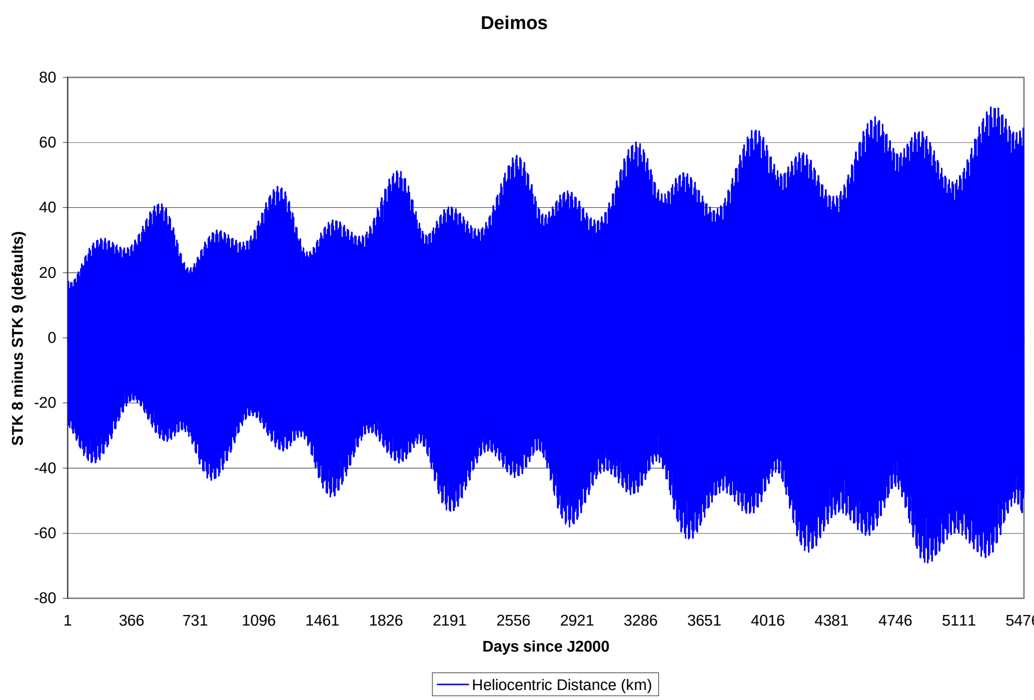
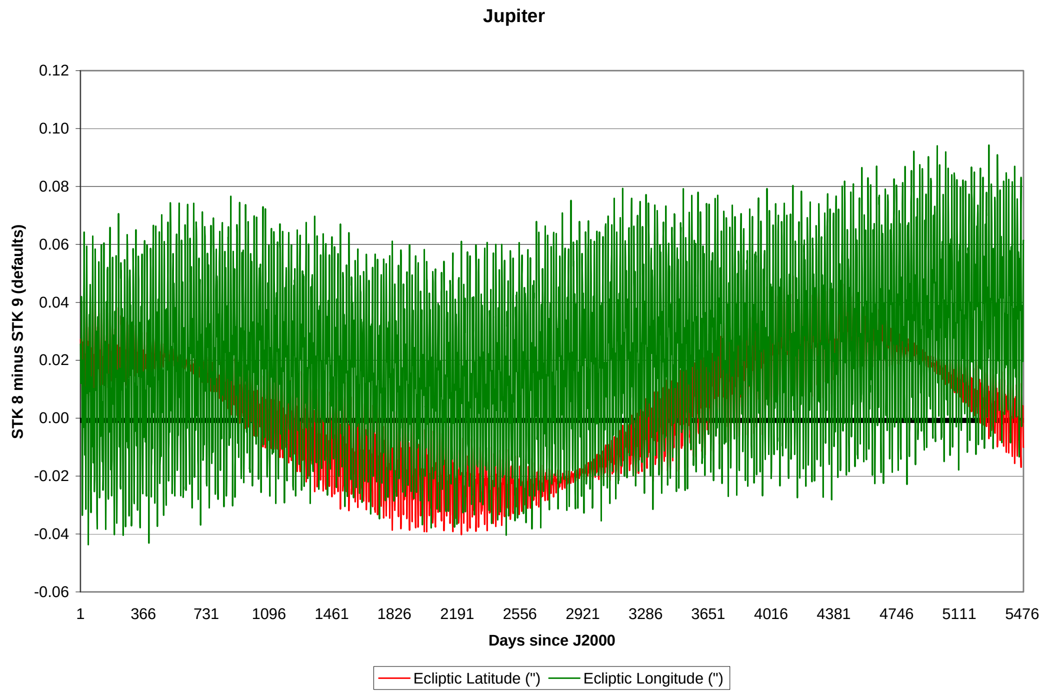


Figure 6. Differences in Reported Deimos Position (2000-2015)



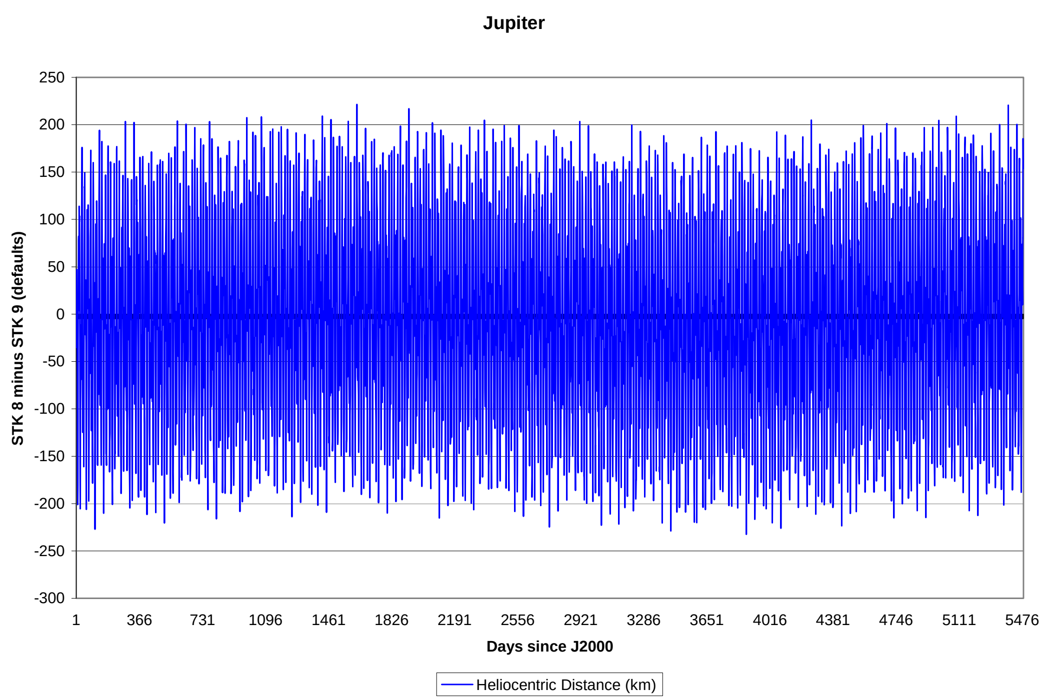
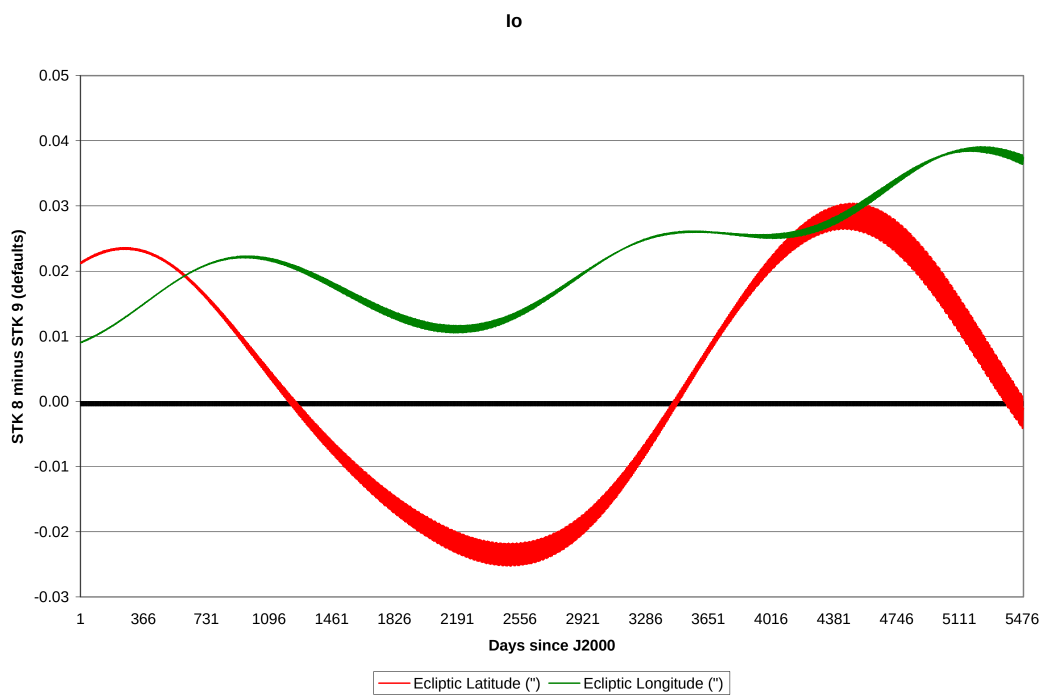


Figure 7. Differences in Reported Jupiter Position (2000-2015)



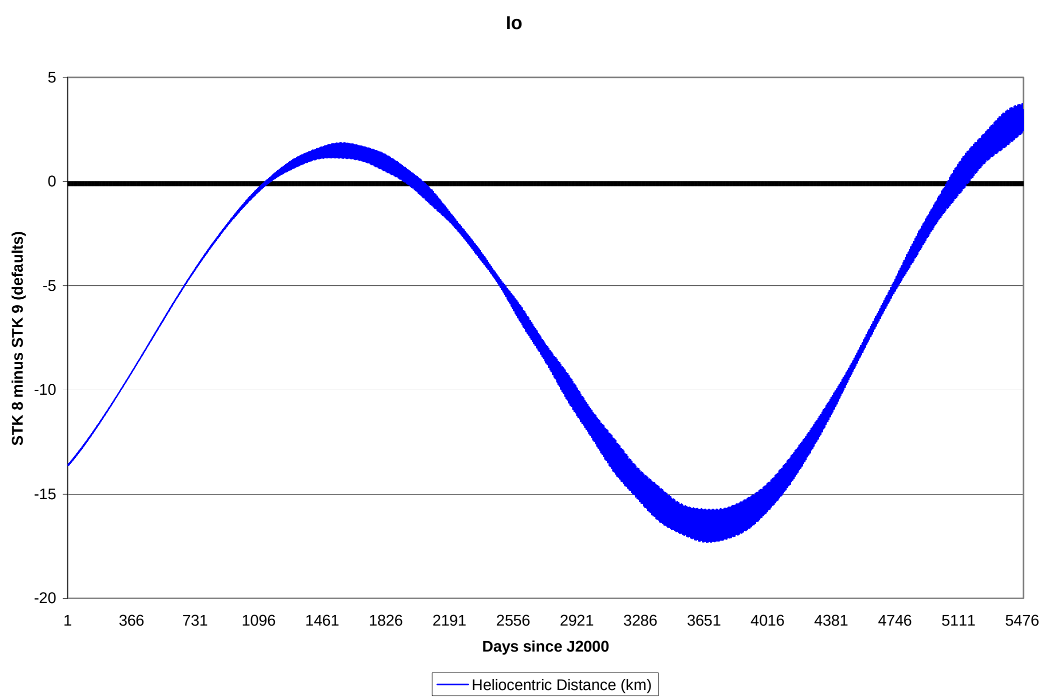
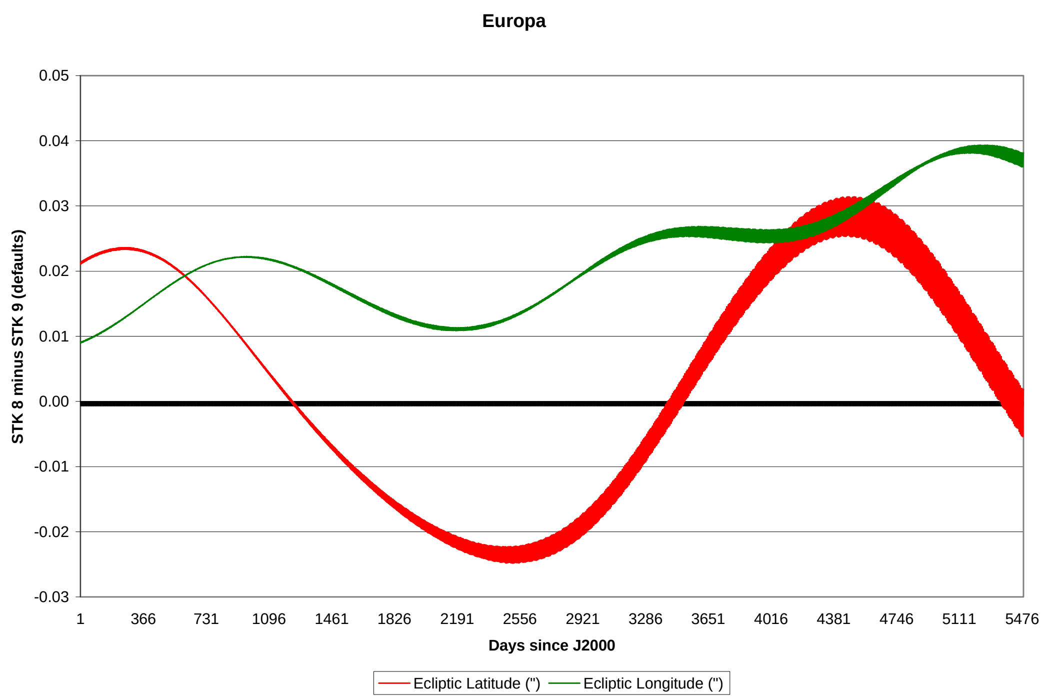


Figure 8. Differences in Reported Io Position (2000-2015)



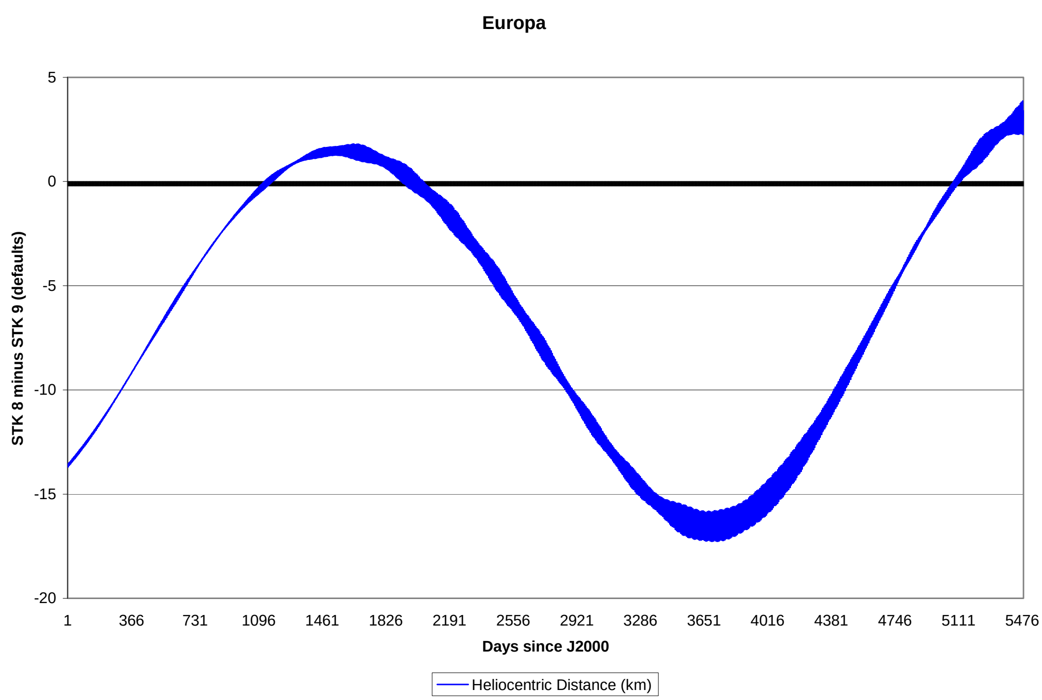
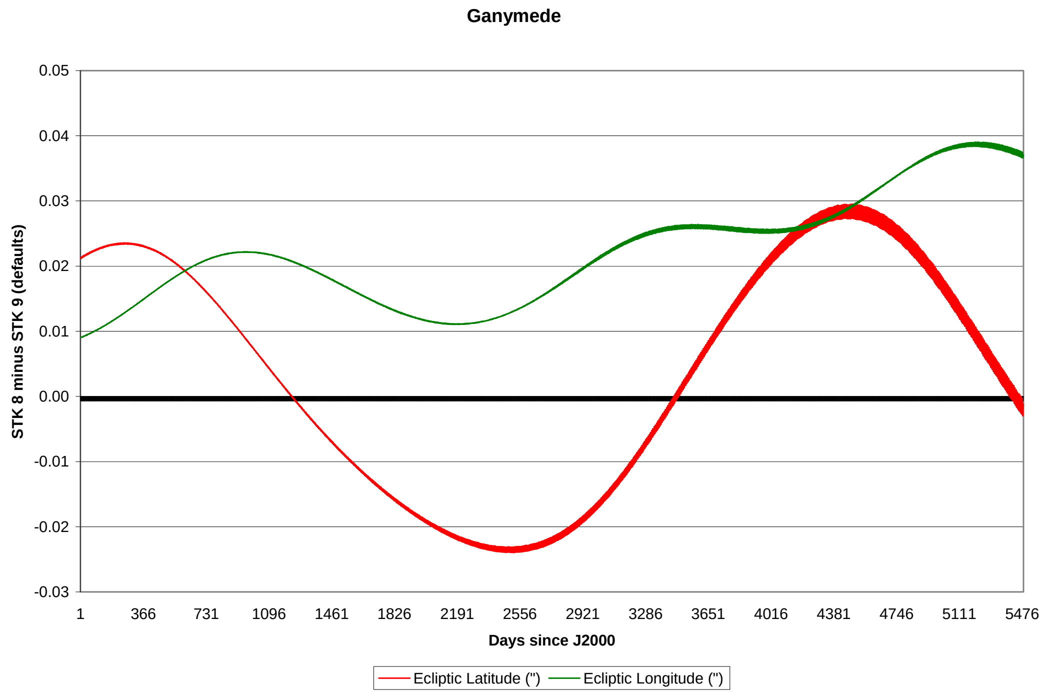


Figure 9. Differences in Reported Europa Position (2000-2015)



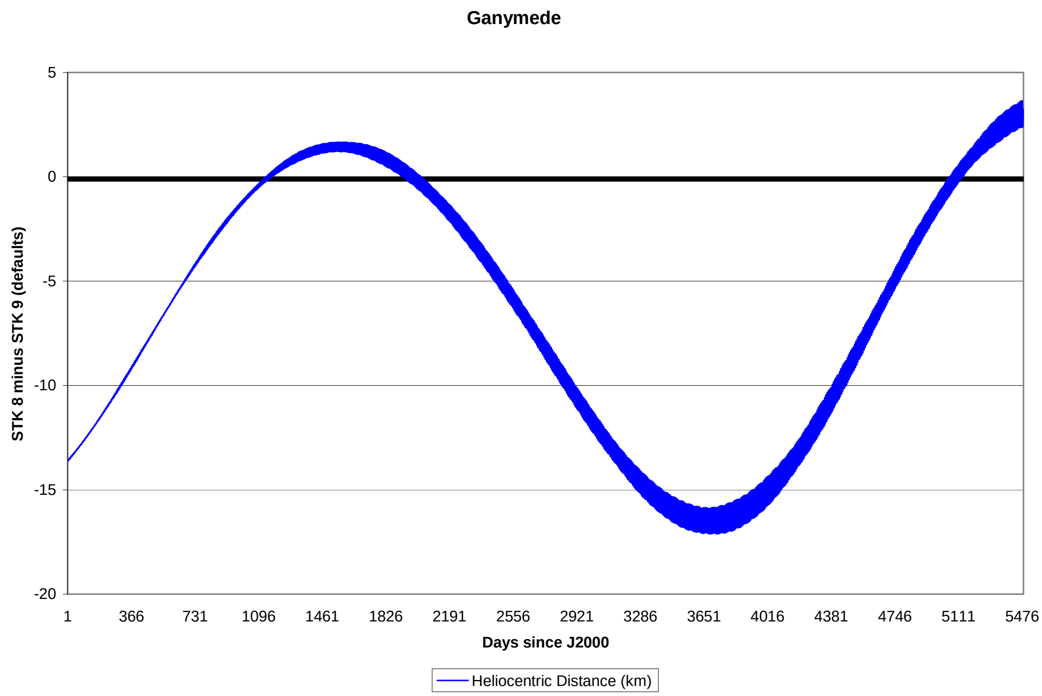
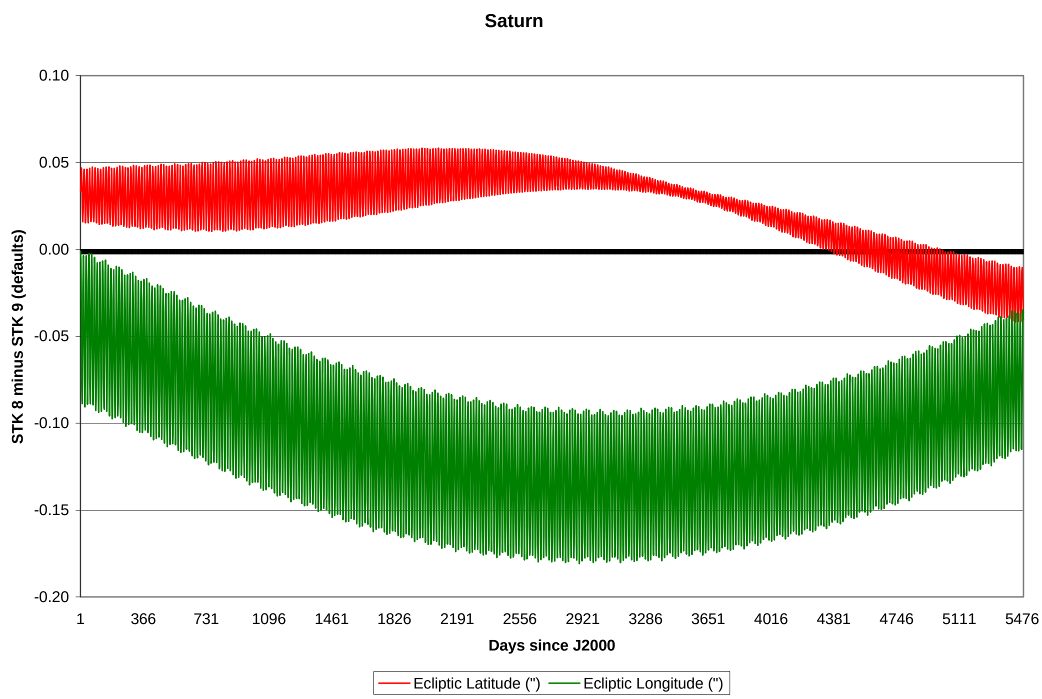


Figure 10. Differences in Reported Ganymede Position (2000-2015)



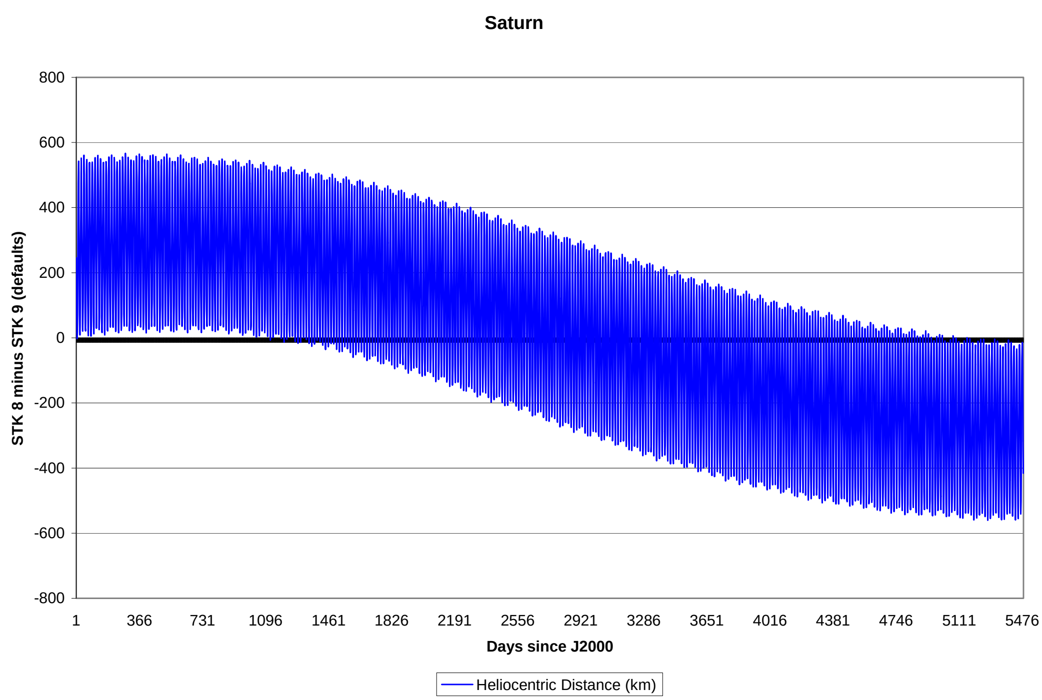
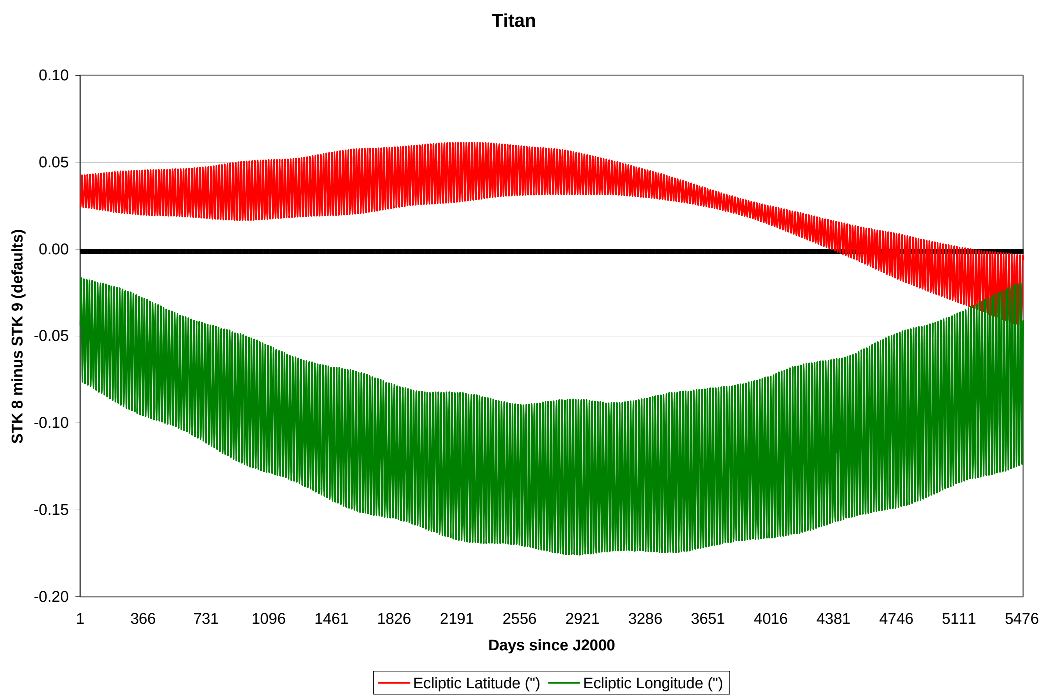


Figure 11. Differences in Reported Saturn Position (2000-2015)



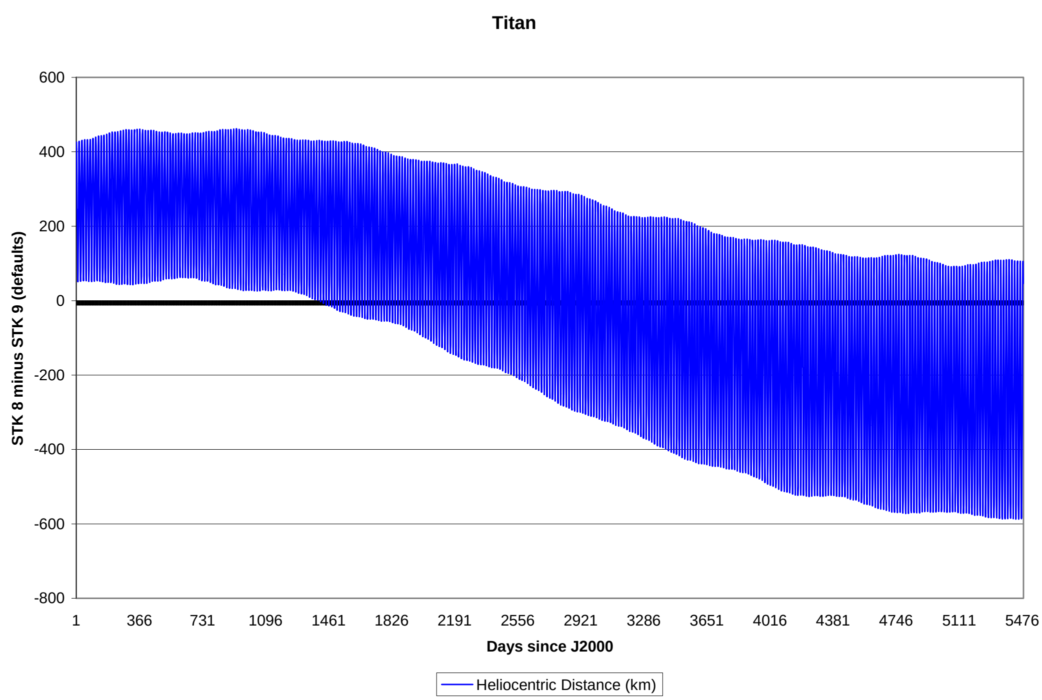
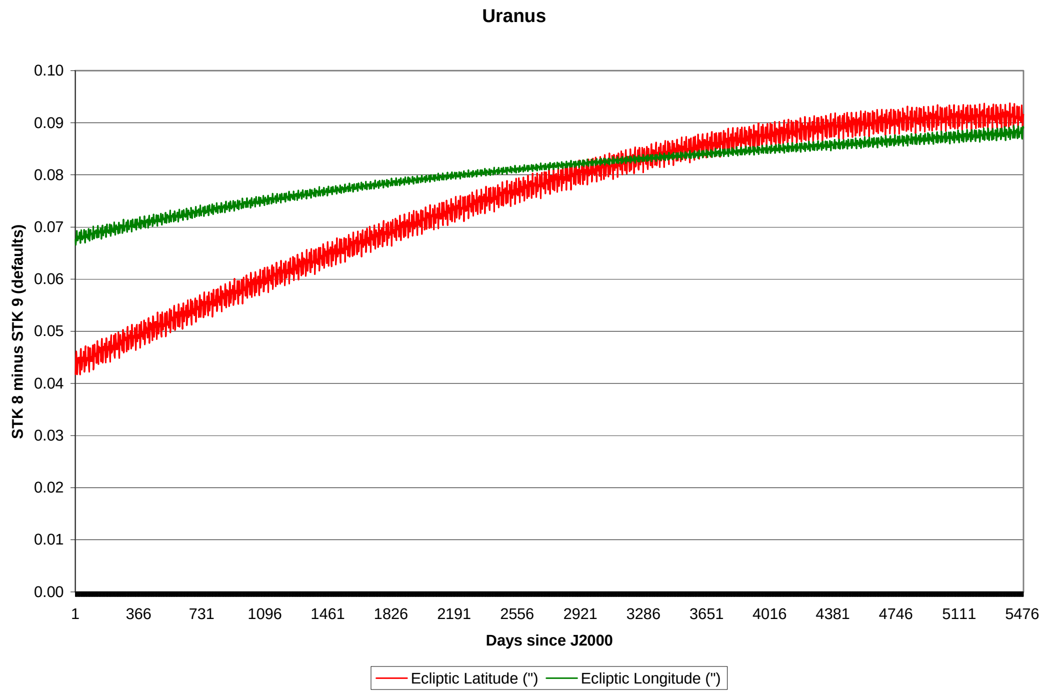


Figure 12. Differences in Reported Titan Position (2000-2015)



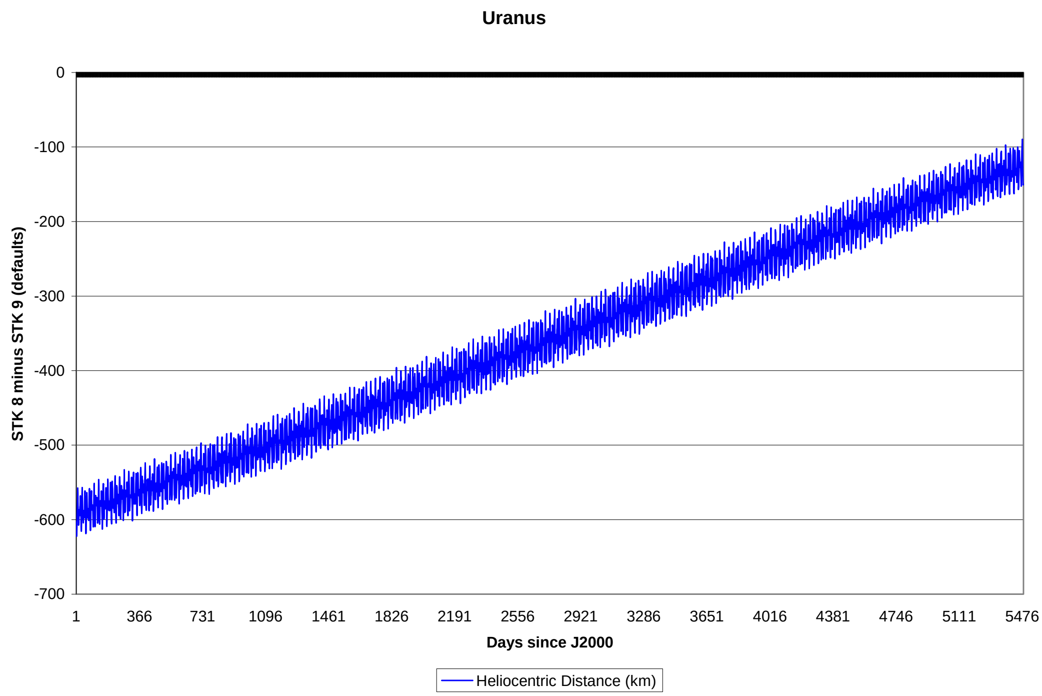
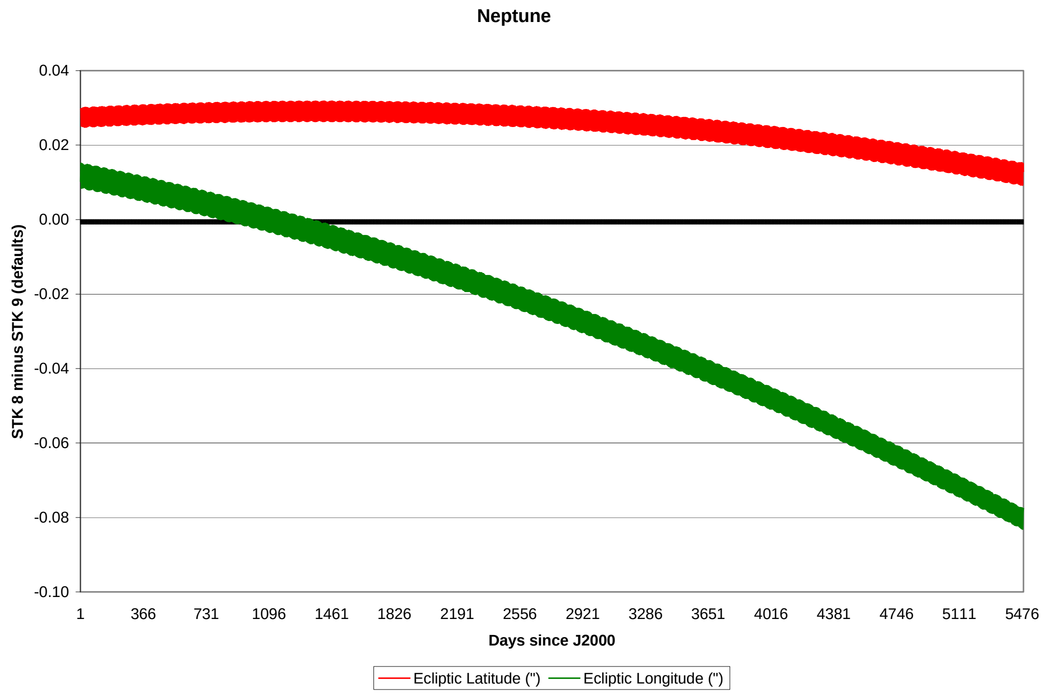


Figure 13. Differences in Reported Uranus Position (2000-2015)



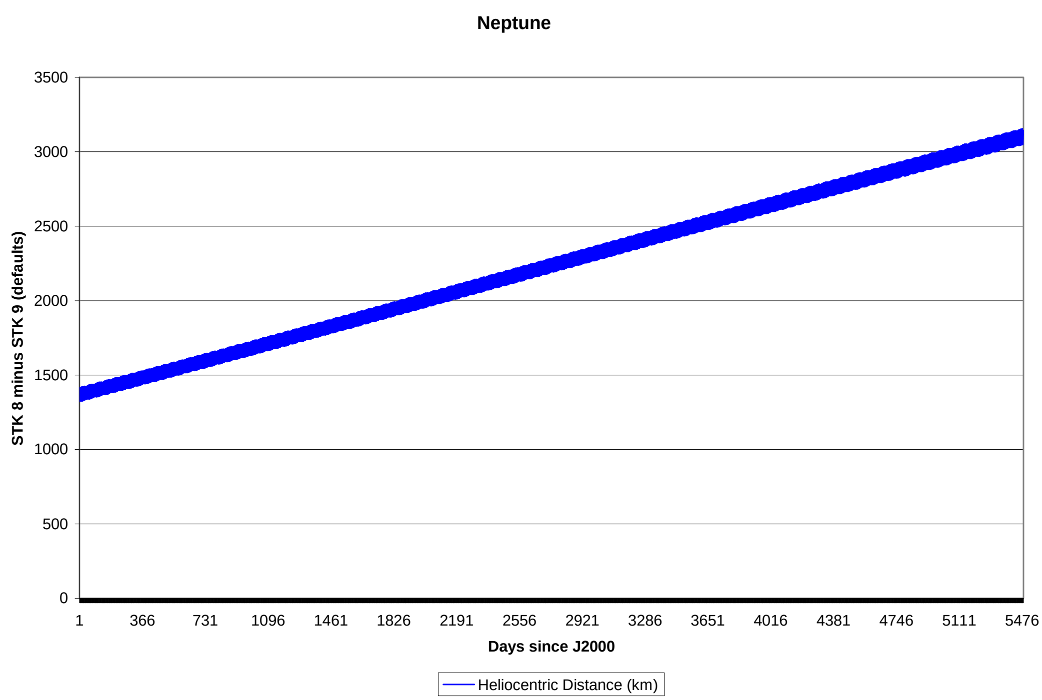
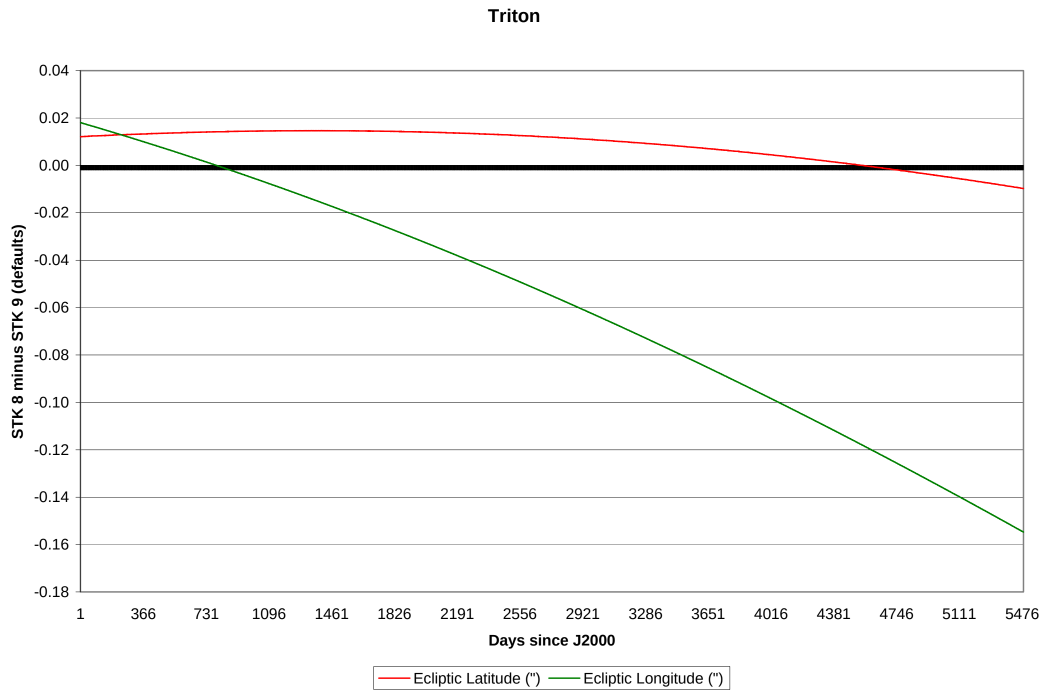


Figure 14. Differences in Reported Neptune Position (2000-2015)



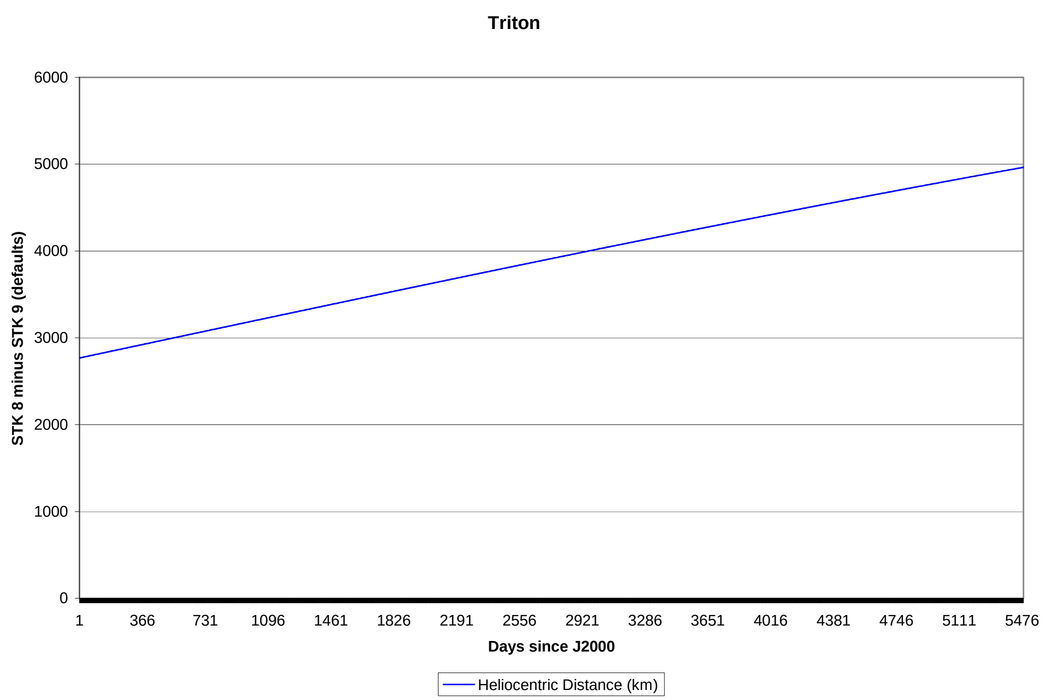
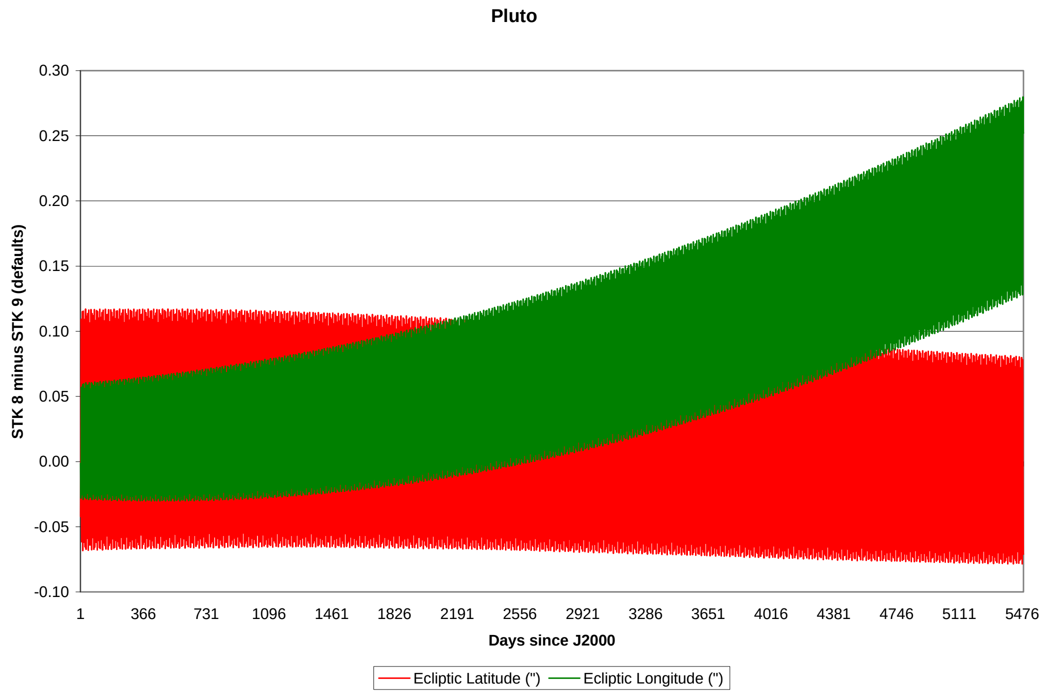


Figure 15. Differences in Reported Triton Position (2000-2015)



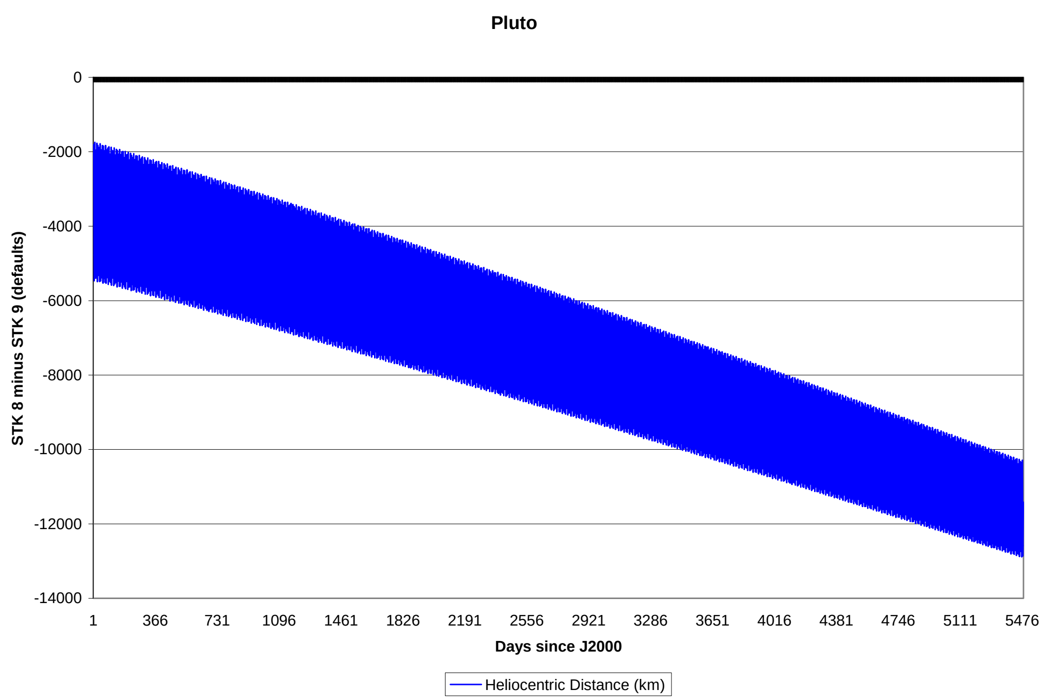
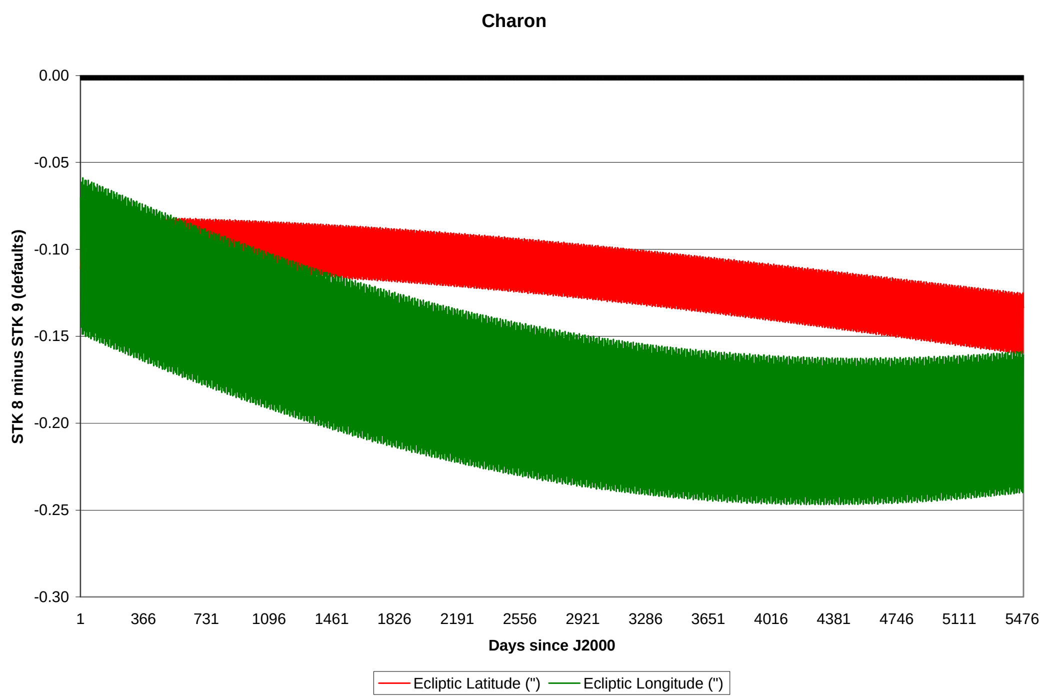


Figure 16. Differences in Reported Pluto Position (2000-2015)



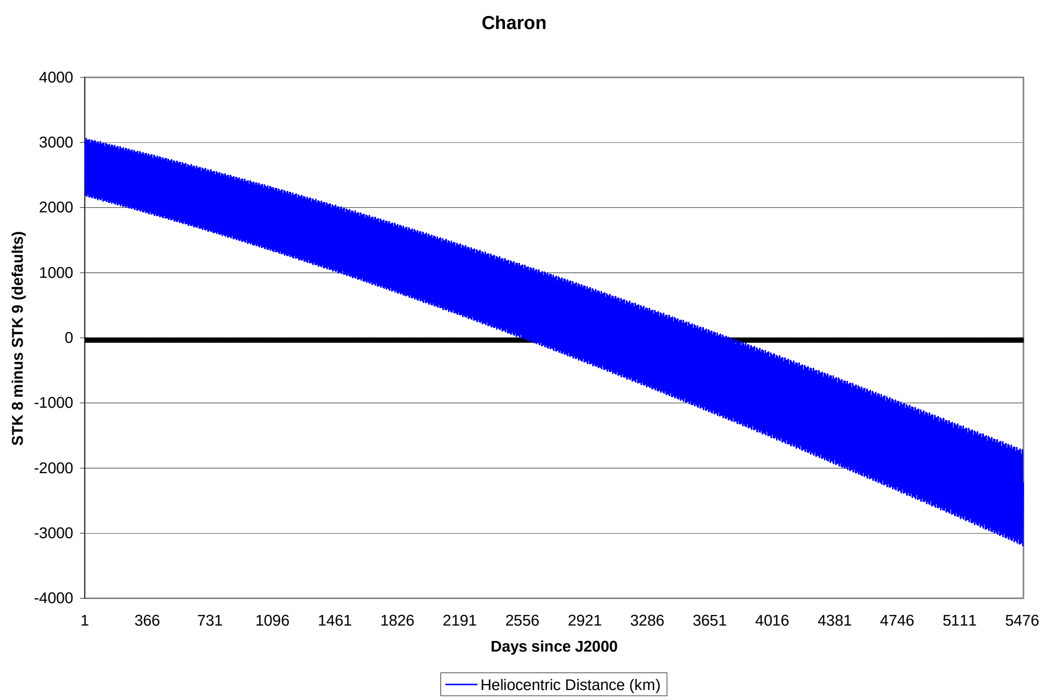


Figure 17. Differences in Reported Charon Position (2000-2015)

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